

**\*\*FULL TITLE\*\***

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## Balancing the Energy Budget: Star-Formation versus AGN in High Redshift Infrared Luminous Galaxies

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**Abstract.** We present deep *Spitzer* mid-infrared spectroscopy, along with 16, 24, 70, and 850  $\mu\text{m}$  photometry, for 22 galaxies located in the Great Observatories Origins Deep Survey-North (GOODS-N) field. The sample spans a redshift range of  $0.6 \lesssim z \lesssim 2.6$ , 24  $\mu\text{m}$  flux densities between  $\sim 0.2\text{--}1.2$  mJy, and consists of submillimeter galaxies (SMGs), X-ray or optically selected active galactic nuclei (AGN), and optically faint ( $z_{AB} > 25$  mag) sources. We find that infrared (IR; 8 – 1000  $\mu\text{m}$ ) luminosities derived by fitting local spectral energy distributions (SEDs) with 24  $\mu\text{m}$  photometry alone are well matched to those when additional mid-infrared spectroscopic and longer wavelength photometric data is used for galaxies having  $z \lesssim 1.4$  and 24  $\mu\text{m}$ -derived IR luminosities typically  $\lesssim 3 \times 10^{12} L_{\odot}$ . However, for galaxies in the redshift range between  $1.4 \lesssim z \lesssim 2.6$ , typically having 24  $\mu\text{m}$ -derived IR luminosities  $\gtrsim 3 \times 10^{12} L_{\odot}$ , IR luminosities are overestimated by an average factor of  $\sim 5$  when SED fitting with 24  $\mu\text{m}$  photometry alone. This result arises partly due to the fact that high redshift galaxies exhibit aromatic feature equivalent widths that are large compared to local galaxies of similar luminosities. Through a spectral decomposition of mid-infrared spectroscopic data, we are able to isolate the fraction of IR luminosity arising from an AGN as opposed to star formation activity. This fraction is only able to account for  $\sim 30\%$  of the total IR luminosity among the entire sample.

### 1 Introduction

The mid-infrared (5 – 40  $\mu\text{m}$ ) SED is a complex interplay of broad emission features thought to arise from polycyclic aromatic hydrocarbon (PAH) molecules, silicate absorption features at 9.7 and 18  $\mu\text{m}$ , and a mid-infrared continuum from very small grains (Leger & Puget 1984; Allamandola, Tielens, & Barker 1985). Mid-infrared luminosities measured near  $\sim 8$   $\mu\text{m}$  have been found to correlate with the total infrared (IR; 8 – 1000) luminosities of galaxies in the local Universe (Chary & Elbaz 2001; Elbaz et al. 2002), which itself is a measure of a galaxy’s SFR. While a correlation is found, there does exist a large amount of scatter (Dale et al. 2005; Smith et al. 2007; Armus et al. 2007) and systematic de-

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partures for low metallicity systems (Engelbracht et al. 2005; Madden et al. 2006). It is therefore uncertain if these empirical relations between mid-infrared and total IR luminosities ( $L_{\text{IR}}$ ) for galaxies in the local Universe are applicable for galaxies at higher redshifts.

Recently, data from deep far-infrared surveys such as the Far-infrared Deep Legacy Survey (FIDEL; PI: M. Dickinson) are confirming the same redshift evolution of the SFR density seen in the mid-infrared and do not show any evolution in the SED of infrared luminous galaxies (e.g. Magnelli et. al. 2009). In contrast, Rigby et al. (2008) have provided evidence that the high redshift lensed mid-infrared selected galaxies might show a factor of  $\sim 2$  stronger rest-frame  $8\text{ }\mu\text{m}$  emission compared to their total IR luminosities.

Using mid-infrared spectroscopy for 22 sources selected at  $24\text{ }\mu\text{m}$  in the GOODS-N field, along with existing  $850\text{ }\mu\text{m}$  and additional  $70\text{ }\mu\text{m}$  imagery obtained as part of FIDEL, we aim to improve our understanding of the star formation and AGN activity within a diverse group of  $0.6 \lesssim z \lesssim 2.6$  galaxies. This is done through a more proper estimate of IR luminosities and the ability to decompose these measurements into star-forming and AGN components. For the full study, please see Murphy et al. (2009).

## 2 Accuracy of $24\text{ }\mu\text{m}$ -Derived IR Luminosities

By plotting the  $5\text{--}15\text{ }\mu\text{m}$  mid-infrared regions of the four different Chary & Elbaz (2001) fits (see caption) for each galaxy in the left panel of Figure 1, one easily sees that by using  $24\text{ }\mu\text{m}$  flux densities alone the equivalent widths of the aromatic features observed in the IRS spectra are underestimated by the Chary & Elbaz (2001) templates, resulting in highly discrepant estimates (i.e. overestimates) of IR luminosity.

The range of IR luminosities derived by fitting the  $24\text{ }\mu\text{m}$  photometry alone span a range between  $4.3 \times 10^{11} - 4.2 \times 10^{13} L_{\odot}$  (i.e. nearly two orders of magnitude) with a median of  $7.5 \times 10^{12} L_{\odot}$ . Looking at the best-fit estimates for the IR luminosities among the entire sample, we find that they range between  $3.2 \times 10^{11} - 1.1 \times 10^{13} L_{\odot}$  (i.e. a factor of  $\sim 35$ ) having a median of  $2.2 \times 10^{12} L_{\odot}$ . The  $24\text{ }\mu\text{m}$ -derived IR luminosity is a factor of  $\sim 4$  larger than that for the best-fit estimates, on average.

Using our best-fit IR luminosities, we also note that 16 out of the 22 sample galaxies are classified as ULIRGs while the remaining 6 are LIRGs. Looking at the differences between the  $24\text{ }\mu\text{m}$  to our best-fit IR luminosities, the discrepancy is found to be much larger among the ULIRGs than for the LIRGs. The  $24\text{ }\mu\text{m}$ -derived IR luminosities are larger than the best-fit IR luminosities by a factor of  $\sim 5$ , on average, for the ULIRGs while being only  $\sim 1.2$  times larger, on average, for the LIRGs.

## 3 SFR Estimates and the Contribution from AGN

In the right panel of Figure 1 we plot AGN luminosity versus the difference between the  $24\text{ }\mu\text{m}$  and best-fit estimate IR luminosities. A clear trend of increasing AGN luminosity with increasing overestimation of the IR luminosity

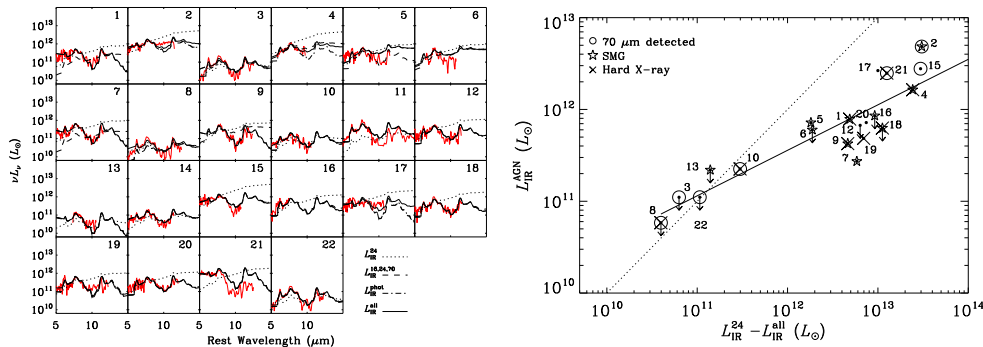


Figure 1. *Left:* A blowup of the 5–15  $\mu\text{m}$  range for the best-fit SEDs of Chary & Elbaz (2001) for all sources using only 24  $\mu\text{m}$  flux densities (*dotted* lines), all 3 *Spitzer* (16, 24, and 70  $\mu\text{m}$ ) flux densities (*dashed* lines), *Spitzer* and submillimeter (850  $\mu\text{m}$ ) photometry (*dot-dashed* lines), and all photometry (*Spitzer* and submillimeter) along with the IRS spectra (*solid* lines). The actual spectra, smoothed to the instrumental resolution, are overplotted in red. The SEDs chosen when fitting with the 24  $\mu\text{m}$  data alone rarely characterize the observed PAH emission as compared to when longer wavelength data is included in the fitting. *Right:* The estimated AGN luminosity as a function of the difference between the 24  $\mu\text{m}$  and best-fit IR luminosities. Sources for which only upper limits to the AGN mid-infrared luminosity fraction could be determined are shown as *downward arrows*. An ordinary least squares fit is overplotted as a *solid* line while the *dotted* line indicates a one-to-one relationship to show that the AGN luminosity is not able to account for the difference in the bolometric correction when fitting the SED templates with 24  $\mu\text{m}$  photometry alone.

using 24  $\mu\text{m}$  photometry alone is observed; or, in other words, AGN luminosity appears to scale with increasing mid-infrared luminosity. Performing an ordinary least squares fit to the data, we find that

$$\log \left( \frac{L_{\text{IR}}^{\text{AGN}}}{L_\odot} \right) = (0.50 \pm 0.04) \log \left( \frac{L_{\text{IR}}^{24} - L_{\text{IR}}^{\text{all}}}{L_\odot} \right) + (5.61 \pm 0.52). \quad (1)$$

While the differences between the 24  $\mu\text{m}$  and best-fit IR luminosities are large for galaxies having large (i.e.  $\gtrsim 60\%$ ) mid-infrared AGN fractions, we find these quantities to be unrelated for galaxies having smaller mid-infrared AGN fractions. We also find that the AGN luminosity accounts for only 16% of the difference between the 24  $\mu\text{m}$  derived and best-fit IR luminosities, on average. This indicates that the AGN contribution to the mid-infrared excesses, which would result in overestimates of IR-based SFRs, is close to negligible when compared to the improper bolometric correction applied when estimating total IR luminosities by fitting local SED templates with 24  $\mu\text{m}$  data alone. SFRs derived by subtracting the AGN fraction from the 24  $\mu\text{m}$  photometry are larger than the AGN corrected best-fit IR SFRs by a factor of  $\sim 1$  to  $\sim 3.3$ , on average for redshifts below and above  $z \sim 1.4$ , respectively. Furthermore, the AGN-corrected 24  $\mu\text{m}$  SFRs are factors of  $\sim 1$  to  $\sim 68$  times larger than the corresponding UV-corrected SFRs for sample galaxies at redshifts above  $z \sim 1.4$ . Therefore, the AGN is not the dominant source of the inferred “mid-infrared excesses” (see Daddi et al. 2007) among these systems.

## 4 Conclusions

In the present study we have used observations from the mid-infrared to the submillimeter to properly characterize the IR luminosities for a diverse sample of 22 galaxies spanning a redshift range of  $0.6 \lesssim z \lesssim 2.6$ . In addition, we have used the mid-infrared spectra of these sources to estimate the fractions of their IR luminosities which arise from an AGN. Our conclusions can be summarized as follows:

1. IR ( $8 - 1000 \mu\text{m}$ ) luminosities derived by SED fitting observed  $24 \mu\text{m}$  flux densities alone are well matched to those when additional mid-infrared spectroscopy and 16, 70, and  $850 \mu\text{m}$  photometry are included in the fits for galaxies having  $z \lesssim 1.4$  and  $L_{\text{IR}}^{24}$  values typically  $\lesssim 3 \times 10^{12} L_{\odot}$ . In contrast, for galaxies lying in a redshift range between 1.4 and 2.6 with  $L_{\text{IR}}^{24}$  values typically  $\gtrsim 3 \times 10^{12} L_{\odot}$ , IR luminosities derived by SED template fitting using observed  $24 \mu\text{m}$  flux densities alone overestimate the true IR luminosity by a factor of  $\sim 5$ , on average, compared to fitting all available data. A comparison between the observed mid-infrared spectra with that of the SEDs chosen from fitting  $24 \mu\text{m}$  photometry alone and from fitting all available photometric data demonstrates that local high luminosity SED templates show weaker PAH emission by an average factor of  $\sim 5$  in this redshift range and do not properly characterize the contribution from PAH emission.
2. After decomposing the IR luminosity into star forming and AGN components, we find the AGN luminosity to be increasing with increasing difference between the  $24 \mu\text{m}$ -derived and our best-fit IR luminosities. Such a trend suggests that the AGN power increases with mid-infrared luminosity. However, we also find that the median fraction of the AGN to the difference between the  $24 \mu\text{m}$ -derived and best-fit IR luminosities is only 16% suggesting the AGN power is almost negligible compared to the bolometric correction necessary to properly calibrate the  $24 \mu\text{m}$ -derived IR luminosities.

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